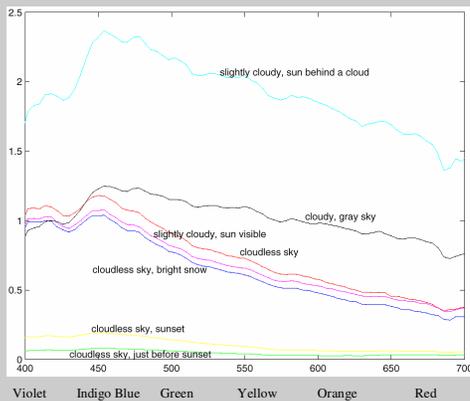
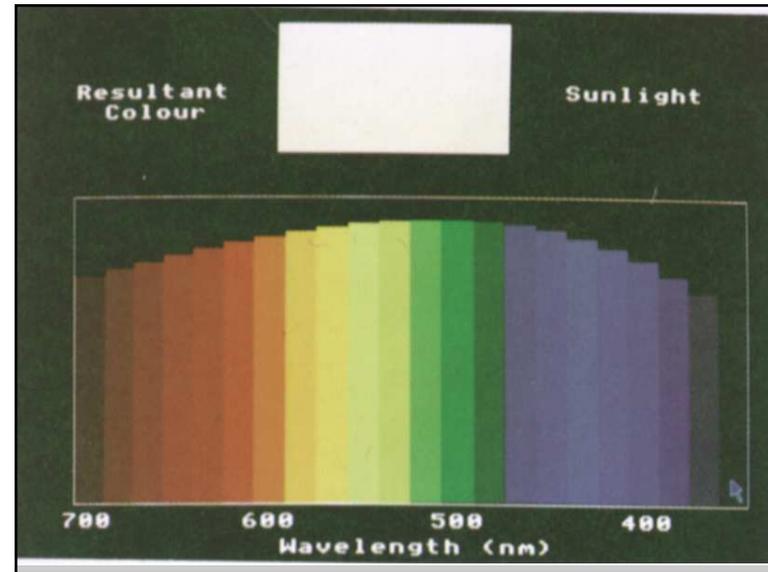


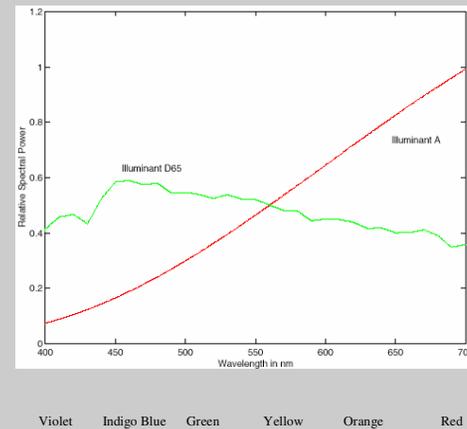
Color and Shading

CS-184: Computer Graphics

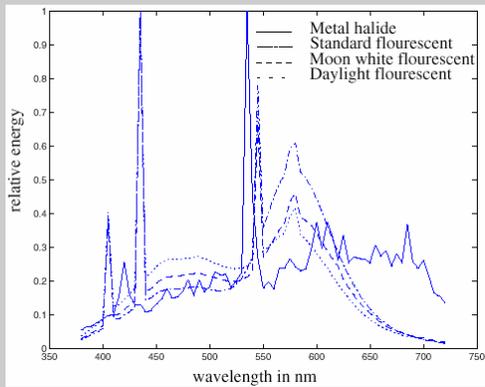
Prof. James O'Brien



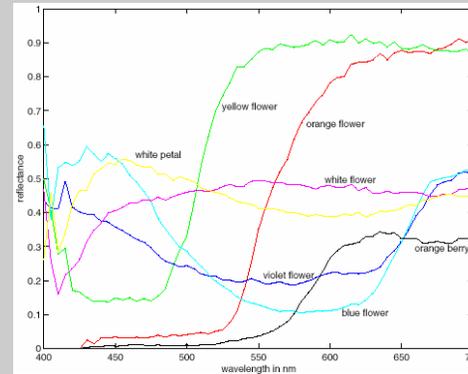
Measurements of relative spectral power of sunlight, made by J. Parkkinen and P. Silfsten. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the "colors of the rainbow". Mnemonic is "Richard of York got blisters in Venice".



Relative spectral power of two standard illuminant models --- D65 models sunlight, and illuminant A models incandescent lamps. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the "colors of the rainbow".



Measurements of relative spectral power of four different artificial illuminants, made by H.Sugiura. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm.

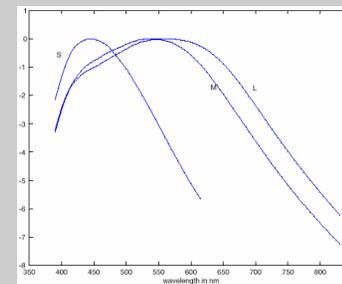


Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

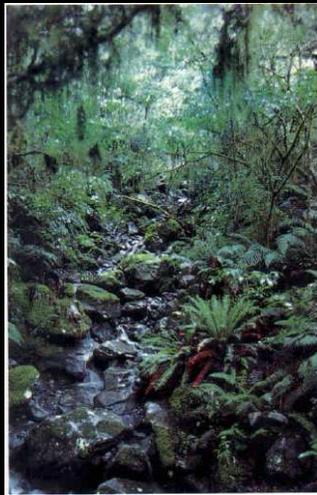
The appearance of colors

- Color appearance is strongly affected by (at least):
 - other nearby colors,
 - adaptation to previous views
 - “state of mind”
- **Film color mode:**
 - View a colored surface through a hole in a sheet, so that the color looks like a film in space; controls for nearby colors, and state of mind.
- **Other modes:**
 - Surface colour
 - Volume colour
 - Mirror colour
 - Illuminant colour

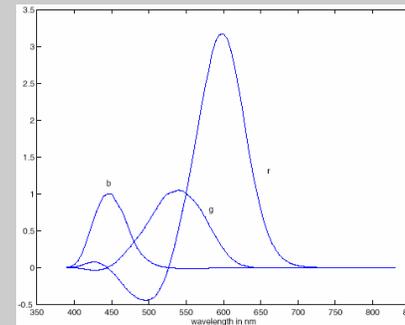
Color receptors



- Plot shows relative sensitivity as a function of wavelength, for the three cones. The S (for short) cone responds most strongly at short wavelengths; the M (for medium) at medium wavelengths and the L (for long) at long wavelengths.
- These are occasionally called B, G and R cones respectively, but that’s misleading - you don’t see red because your R cone is activated.



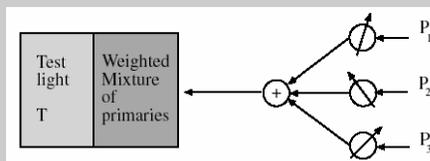
Color matching



RGB: primaries are monochromatic, energies are 645.2nm, 526.3nm, 444.4nm. Color matching functions have negative parts -> some colors can be matched only subtractively.

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Color matching experiments - I



- Show a split field to subjects; one side shows the light whose color one wants to measure, the other a weighted mixture of primaries (fixed lights).
- Each light is seen in film color mode.

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Color matching experiments - II

- Many colors can be represented as a mixture of A, B, C
- write $M = aA + bB + cC$ where the = sign should be read as “matches”
- This is **additive** matching.
- Gives a color description system - two people who agree on A, B, C need only supply (a, b, c) to describe a color.

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Subtractive matching

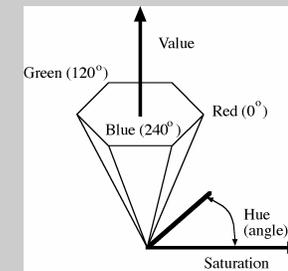
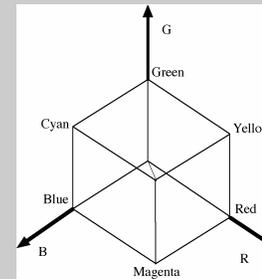
- Some colors can't be matched like this:
instead, must write

$$M+a A = b B+c C$$

- This is **subtractive** matching.
- Interpret this as $(-a, b, c)$
- Problem for building monitors: Choose R, G, B such that positive linear combinations match a large set of colors

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HSV hexcone



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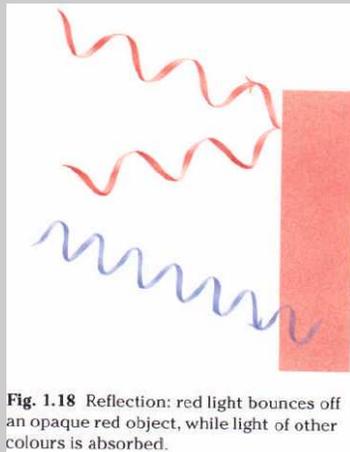


Fig. 1.18 Reflection: red light bounces off an opaque red object, while light of other colours is absorbed.

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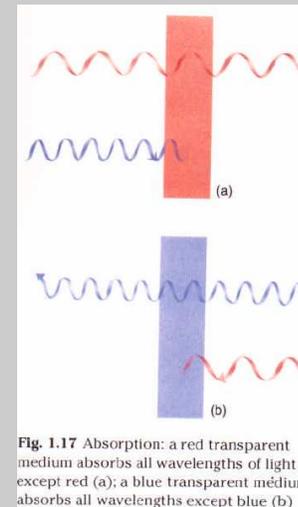


Fig. 1.17 Absorption: a red transparent medium absorbs all wavelengths of light except red (a); a blue transparent medium absorbs all wavelengths except blue (b)

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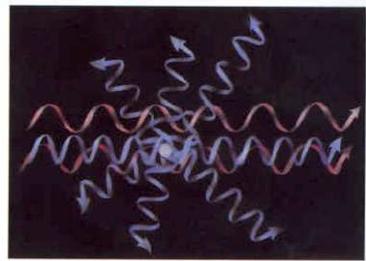


Fig. 1.25 Rayleigh scattering: when particles in air or water are small relative to light wavelength they scatter blue light preferentially.

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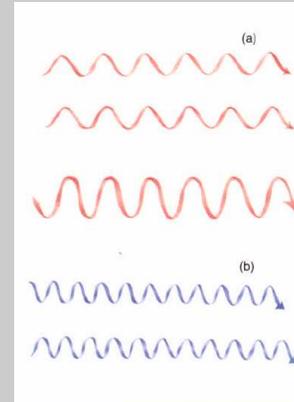


Fig. 1.20 Interference: when two light waves are in phase, they interfere positively to reinforce each other and produce a wave with double the intensity of colour (a). When two waves are out of phase they cancel each other and no colour is seen (b).

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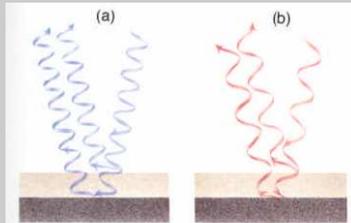
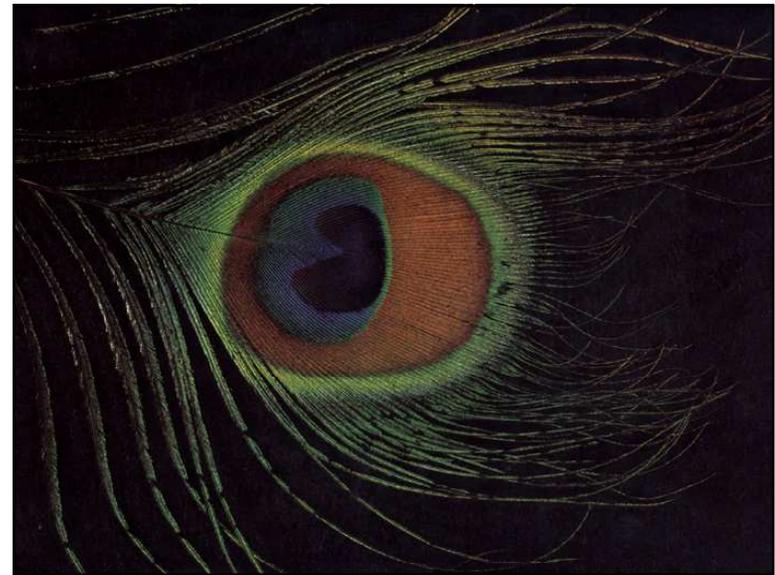
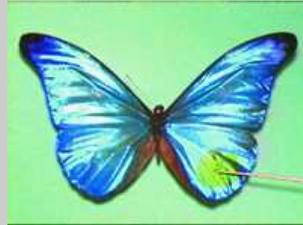
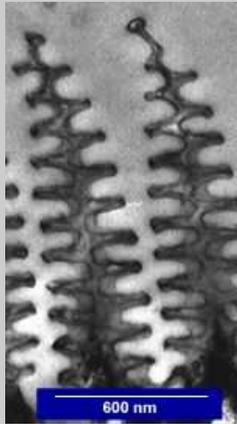


Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at the surface. In this case the blue waves are in phase and their colour is reinforced (a) but the red waves are out of phase and their colour is cancelled (b).

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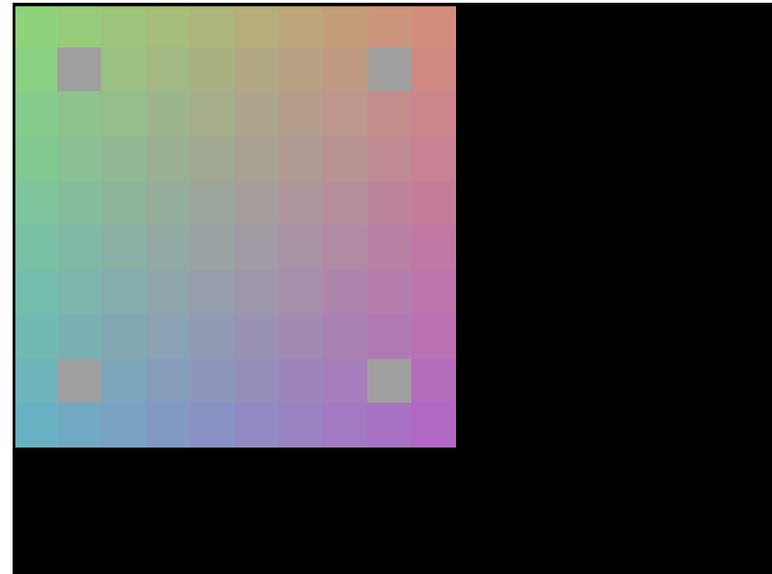
Black body radiators

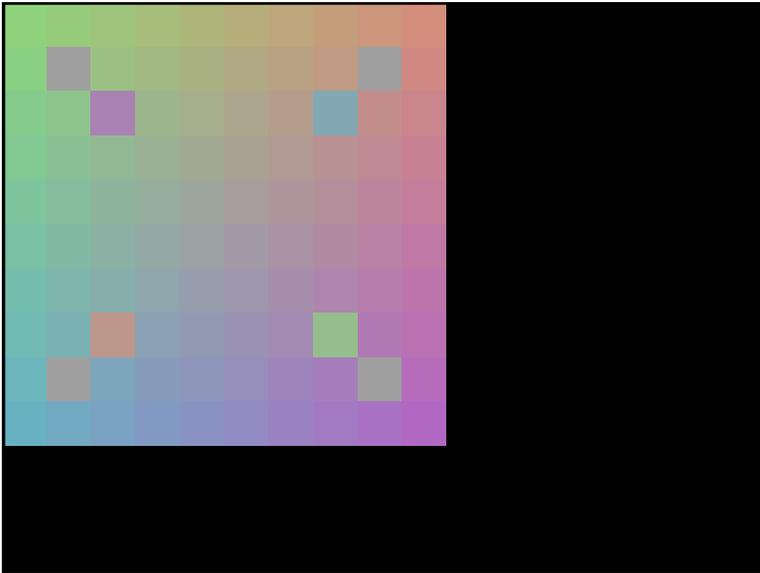
- Construct a hot body with near-zero albedo (black body)
 - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature

$$E(\lambda) \propto \left(\frac{1}{\lambda^5}\right) \left(\frac{1}{\exp(hc/k\lambda T) - 1}\right)$$

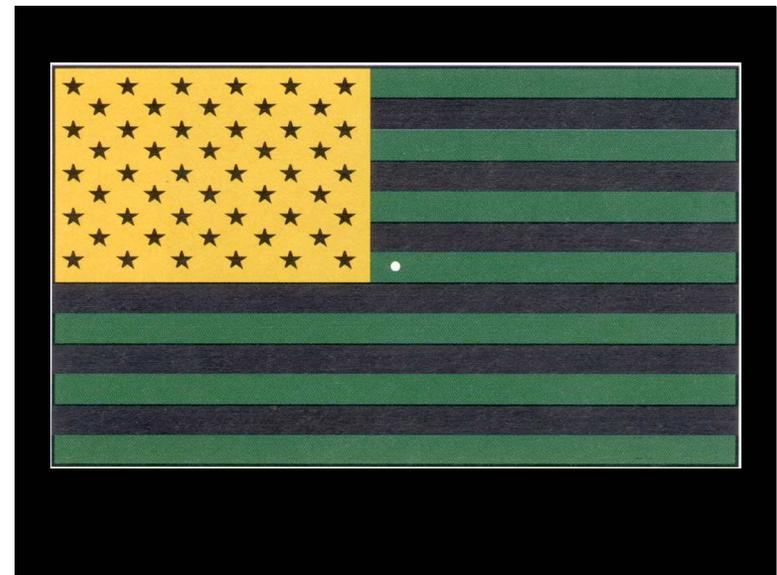
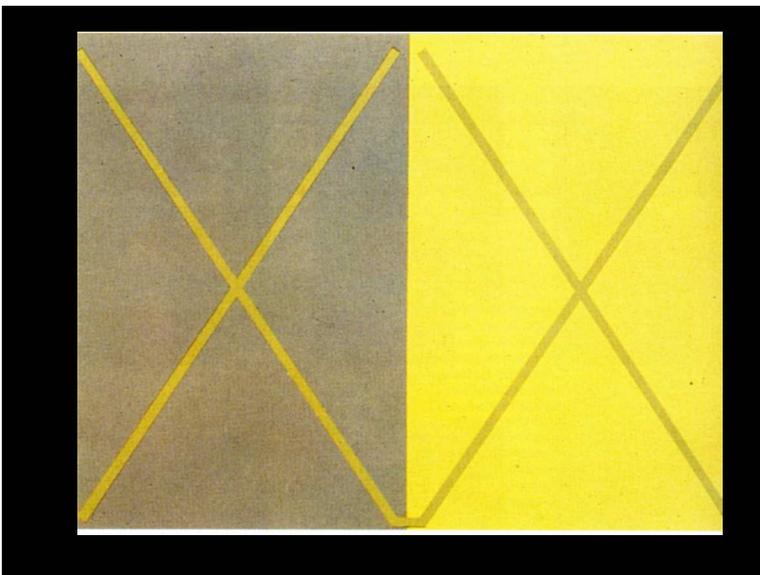
- This leads to the notion of color temperature --- the temperature of a black body that would look the same

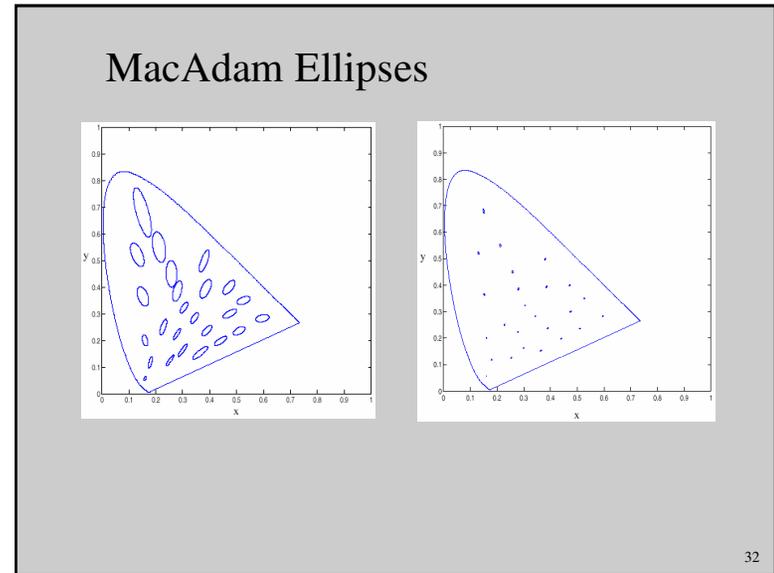
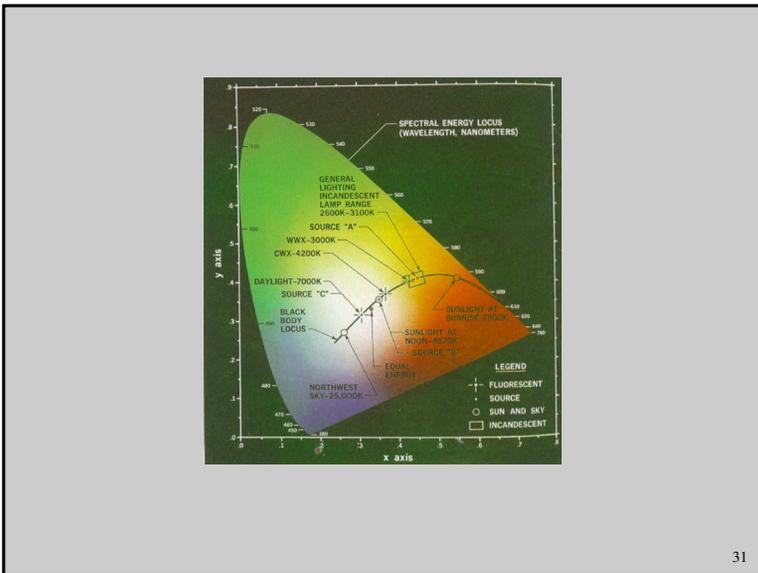
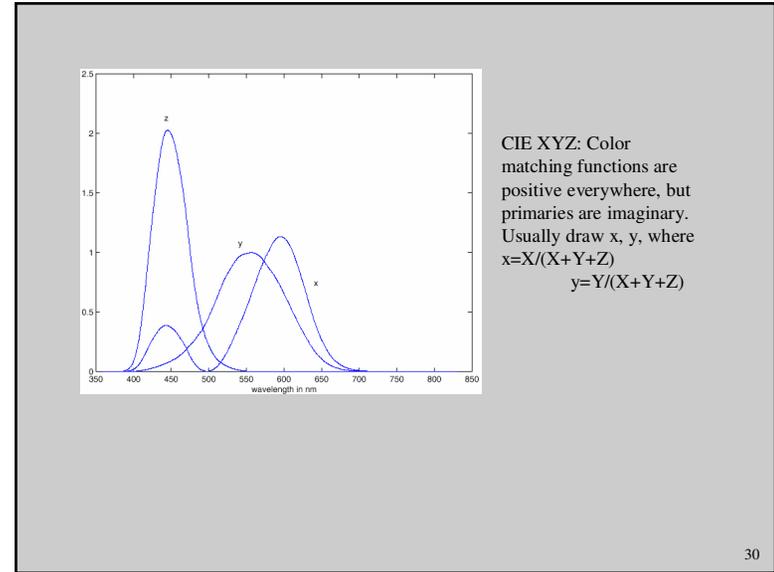
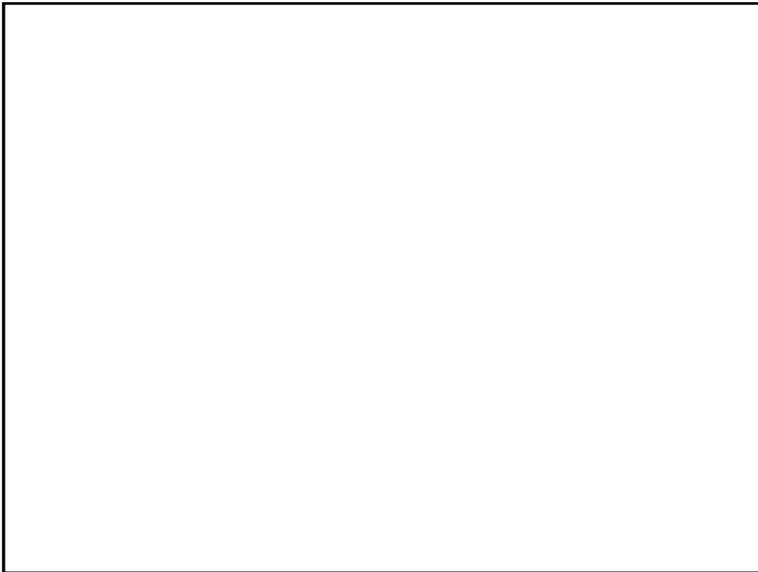
23

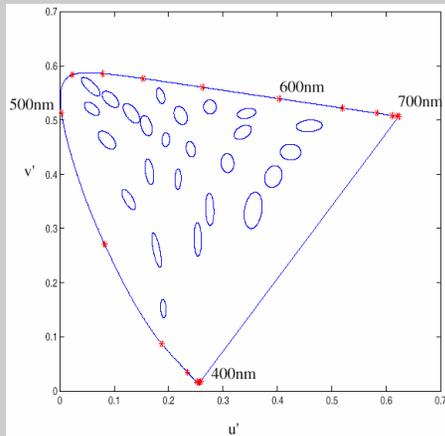




XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	RED	RED
XXXXXX	WHITE	WHITE
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	BLUE	BLUE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	WHITE	WHITE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE

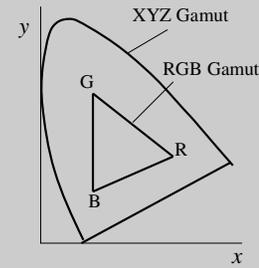






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Determining Gamuts



- Gamut: The range of colors that can be represented or reproduced
- Plot the matching coordinates for each primary. eg R, G, B
- Region contained in triangle (3 primaries) is gamut
- Really, it's a 3D thing, with the color cube distorted and embedded in the XYZ gamut

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Normal Vectors

- The intensity of a surface depends on its orientation with respect to the light and the viewer
 - CDs are an extreme example
- The *surface normal vector* describes the orientation of the surface at a point
 - Mathematically: Vector that is perpendicular to the tangent plane of the surface
 - What's the problem with this definition?
 - Just "the normal vector" or "the normal"
 - Will use n or N to denote
- Normals are either supplied by the user or automatically computed

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Transforming Normal Vectors

- Normal vectors are *directions*
 - Normal vectors are perpendicular to tangent vectors : $\mathbf{n} \cdot (\mathbf{x} - \mathbf{p}) = 0$
 - There is a matrix form of this : $\mathbf{n}'(\mathbf{x} - \mathbf{p}) = 0$
 - Consider the equation with a transformed tangent : $\mathbf{n}'\mathbf{T}(\mathbf{x} - \mathbf{p}) = 0$
 - The right hand half is the transformed point.
 - The new transpose normal must be equal to : $\mathbf{n}'\mathbf{T}^{-1}$
 - The new normal must then be : $(\mathbf{n}'\mathbf{T}^{-1})' = (\mathbf{T}^{-1})'\mathbf{n}$
- To transform a normal, multiply it by the inverse transpose of the transformation matrix
- Recall, rotation matrices are their own inverse transpose
- Don't include the translation!

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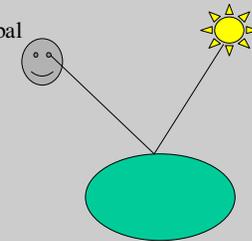
Local Shading Models

- *Local shading models* provide a way to determine the intensity and color of a point on a surface
 - The models are local because they **don't consider other objects**
 - We use them because they are fast and simple to compute
 - They do not require knowledge of the entire scene, only the current piece of surface. Why is this good?
- For the moment, assume:
 - We are applying these computations at a particular point on a surface
 - We have a normal vector for that point

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Local Shading Models

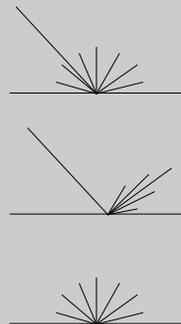
- What they capture:
 - Direct illumination from light sources
 - *Diffuse* and *Specular* components
 - (Very) Approximate effects of global lighting
- What they don't do:
 - Shadows
 - Mirrors
 - Refraction
 - Lots of other stuff ...



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“Standard” Lighting Model

- Consists of three terms linearly combined:
 - *Diffuse* component for the amount of incoming light reflected equally in all directions
 - *Specular* component for the amount of light reflected in a mirror-like fashion
 - *Ambient* term to approximate light arriving via other surfaces

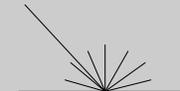


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Diffuse Illumination

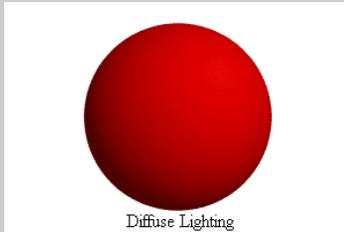
$$k_d I_i (\mathbf{L} \cdot \mathbf{N})$$

- Incoming light, I_i , from direction L , is reflected equally in all directions
 - No dependence on viewing direction
- Amount of light reflected depends on: $k_d I_i \text{abs}(\mathbf{L} \cdot \mathbf{N}, 0)$
 - Angle of surface with respect to light source
 - Actually, determines how much light is collected by the surface, to then be reflected
 - Diffuse reflectance coefficient of the surface, k_d
- Don't want to illuminate back side. Use



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Diffuse Example

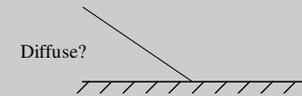


Where is the light?

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Illustrating Shading Models

- Show the polar graph of the amount of light leaving for a given incoming direction:



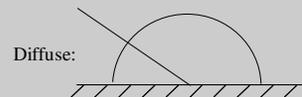
- Show the intensity of each point on a surface for a given light position or direction



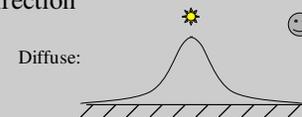
42

Illustrating Shading Models

- Show the polar graph of the amount of light leaving for a given incoming direction:



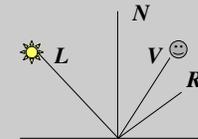
- Show the intensity of each point on a surface for a given light position or direction



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Specular Reflection

(Phong Model)

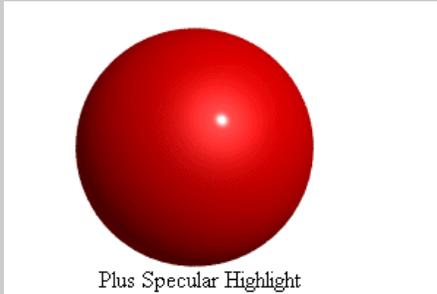


$$k_s I_i (\mathbf{R} \cdot \mathbf{V})^p$$

- Incoming light is reflected primarily in the mirror direction, \mathbf{R}
 - Perceived intensity depends on the relationship between the viewing direction, \mathbf{V} , and the mirror direction
 - Bright spot is called a *specularity*
- Intensity controlled by:
 - The specular reflectance coefficient, k_s
 - The *Phong Exponent*, p , controls the apparent size of the specularity
 - Higher n , smaller highlight

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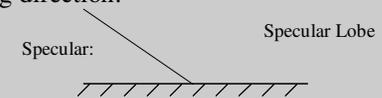
Specular Example



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Illustrating Shading Models

- Show the polar graph of the amount of light leaving for a given incoming direction:



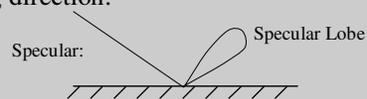
- Show the intensity of each point on a surface for a given light position or direction



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Illustrating Shading Models

- Show the polar graph of the amount of light leaving for a given incoming direction:



- Show the intensity of each point on a surface for a given light position or direction



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Specular Reflection (Cheap version)

$$\mathbf{H} = (\mathbf{L} + \mathbf{V}) / \|\mathbf{L} + \mathbf{V}\|$$

$$k_s I_i (\mathbf{H} \cdot \mathbf{N})^p$$



- Compute based on normal vector and “halfway” vector, \mathbf{H}
 - Always positive when the light and eye are above the tangent plane
 - Not quite the same result as the other formulation

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Putting It Together

$$I = k_a I_a + I_i (k_d (\mathbf{L} \cdot \mathbf{N}) + k_s (\mathbf{H} \cdot \mathbf{N})^p)$$

- Global ambient intensity, I_a :
 - Gross approximation to light bouncing around of all other surfaces
 - Modulated by ambient reflectance k_a
- Just sum all the terms
- If there are multiple lights, sum contributions from each light
- Several variations, and approximations ...

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Color

$$I_r = k_{a,r} I_{a,r} + I_{i,r} (k_{d,r} (\mathbf{L} \cdot \mathbf{N}) + k_{s,r} (\mathbf{H} \cdot \mathbf{N})^n)$$

- Do everything for three colors, r, g and b
- Note that some terms (the expensive ones) are constant
- For reasons we will not go into, this is an approximation, but few graphics practitioners realize it

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Distant Light Approximation

- The viewer direction, \mathbf{V} , and the light direction, \mathbf{L} , depend on the surface position being considered, \mathbf{x}
- Distant light approximation:
 - Assume \mathbf{L} is constant for all \mathbf{x}
 - Good approximation if light is distant, such as sun
 - Generally called a *directional light source*
- What aspects of surface appearance are affected by this approximation?
 - Diffuse?
 - Specular?

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